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An Algorithm of a Convectional Factory Electric Tray Dryer

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ABSTRACT

An algorithm of a convectional factory tray dryer with performance evaluation on the functionality of the dryer was reported. This is required to reduce drying time of material as well as man-machine interface which can cause slow operation and contamination of the material been dried. The algorithm of the model was developed with an interface accorded with computer software (MATLAB) for its quick implementation. This algorithm was able to predict parameter values needed for dryer automation such as heating element diameter, heating chamber length, pumping power and flow rate of air. Result generated from the algorithm, was found to be of importance in fabrication of a convectional factory electric tray dryer. The algorithm was also validated by manually calculated parameter values. The results were found to be the same, this proved the effectiveness of the algorithm.

Keywords - *drying, electric, heating, blower, bending moment, static pressure*

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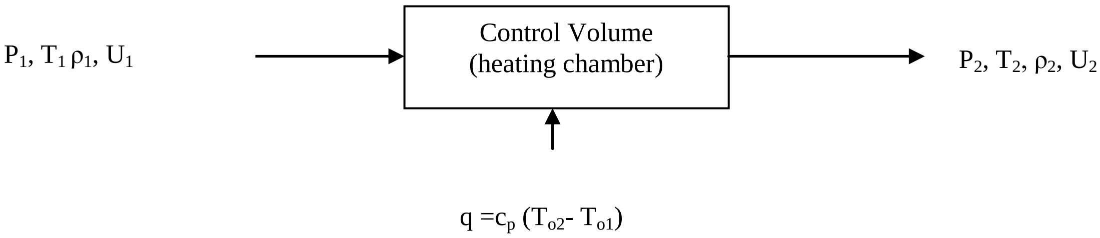
I. INTRODUCTION

The term “drying” is basically utilised in thermal engineering environment which may include food or wood [1]. Drying is an ancient means of preserving food [2]. It is so important in industry because the kinetics of the process can define the final quality properties of the dried material. Haghi and Amanifard, [3] reported that it is a complex process involving simultaneous coupled transient heat, mass and momentum transport. In domestic and industrial parlance, there are many types of dryers, such as: drum dryers, tunnel dryers, tray dryers, drum dryers, fluidized bed dryers, spray dryers, flash dryers, belt dryers, rotary dryers, freeze dryers, and vacuum dryers [2]. Of these dryers, tray dryer is more economical and not complex. The materials to be dried are easily and conveniently dispersed along the surface area of the tray. Drying operations can be broadly classified according to whether they are batch or continuous [4]. These terms are applied specifically from the point of view of the substance being dried. The process term batch drying entails the quantity of the substance being dried passing through a continuous stream of hot flowing air. In the continuous process the substance to be dried as well as the gas passes continually through the equipment. The mechanism involved in batch drying include; constant rate period, falling rate period and equilibrium moisture content. According to Shepherd [5], the rate of evaporation and the surface temperature can be obtained by heat balance. Foust et al.,[6] reported on the graphical models that can be used to describe drying operations. Akpinar, [7] concluded that at every mode of drying route under exanimation, there was no constant-rate period of drying. The rate of drying was reported to be decrease along with the drying time [8]. Economical and rational uses of agricultural produce demands a means for the conservation of excess production. Thus, the need for an effective drier to dry to a predetermined level the moisture contained in agricultural produce such as meat, fish cassava, potatoes. Hence, the present work seeks to establish an algorithm for a convectional factory tray dryer.

1.1 DESIGN CONSIDERATIONS AND ANALYSIS

The automated tray dryer was designed to have the following nomenclature: heating element, the prime mover, fan (blower), control system and algorithm (flow chart).

1.1.1 Overview of Heating Chamber



Design of Heating Element

Heat is radiated from the coil and by means of forced convection is transported to the commodity through a blower. Coil of circular-cross sectional or rectangular ribbons was use as heating elements. Under steady state condition, a heating element dissipates nearly as much heat from its surface as it receives power from the electric supply Theraja,[9]. If P if the power input and it is the heat dissipated by radiation, hence,

P =H (1) (under steady state condition)

From Stefan's law of radiation, heat radiated by a hot body is given by;

$H=5\ .72e^k\ [(T_1/100)^4 - (T_2/100)^4]\ W/m^2$

Now $P = \frac{V^2}{R}$ and R = ρ(L/A) = $\frac{4\rho l}{\pi d^2}$. Therefore, P = $\pi d^2 v^2 / (4\rho l)$ or $l/d^2 = \pi r^2/(4\rho P)$

Where v = the potential gradient (in volts), R= the resistance of the heating element.

Total surface area of the coil element = πdl (2)

If H is the heat dissipated by radiation per seconds per unit area of the coil, the heat radiated per second is;

P = (πdlH) or $\frac{\pi d^2 V^2}{(4\rho l)} = \pi d^2 lH$

Where: d = diameter, l=length, $\rho = \text{density}\ and\ H = \text{heat dissipated}$

Therefore; $\frac{d^2}{l} = \frac{4\rho H}{V^2}$ (3)

1.1.2 Fan Motor Relationship

The fan modeled for this purpose is an axial fan. The model is a function of the following parameters;

Density of fan air

Fan air density is a mass per unit volume of the air. The density of a perfect gas is a function of its molecular weight, temperature and pressure as indicated by

$$\rho_x = (M/386.7)(529.7/T_x)(b_x/29.92) \quad (4)$$

Where M = molecular weight, T_x= temperature and b_x = pressure

For dry air, the above equation reduces to

$$\rho_x = 1.325(b_x/T_x) \quad (5)$$

This equation is valid for moist air.

Capacity of fan

Since the fan is of the axial type, most of our design parameters would be limited to analysis in x- direction therefore; $Q_x = 1.097A_x\sqrt{(\rho v_x/\rho_x)}$ (6)

Thus the total capacity, which is the volumetric flow rate at fan air density ρ_x,

is given as $Q = Q_x\,\rho_x/\rho$ (7)

A more practical value of Q is given as $Q = C\omega R^3$ (8)

The value of Q is limited as demonstrated; A blade has a mean sectional area A and length αR thus, the volume of blade becomes αRA, its acceleration; $\omega^2 R$ and

Centrifugal force F =$\rho(\alpha RA)\omega^2 R$ stress due to force is $F/A = \propto \rho\omega^2 R^2$ (9)

If S_f is the failure stress blade material then the content $\delta \le S_f/n$ (10)

Combining equations (9) and (10), we have

$$\omega \le [S_f/\alpha n\rho]^{\frac{1}{2}}\ {}^1/_R \quad \text{and} \quad Q \le CR^2/(\alpha n)^{\frac{1}{2}}[S_f/\rho]^{\frac{1}{2}} \quad (11)$$

Fan total pressure

Fan total pressure is the differences between the total pressure at the fan outlet and the total pressure at the fan inlet.

$P_t = P_{t2} - P_{t1}$ (12)

If the fan draws air directly from the atmosphere as in this case

$P_{t1} = 0,$ i.e $P_t = P_{t2}$ (13)

If also, the fan is connected to a duct as in the case of our model, the pressure drop ΔP_{2-x} must be added i.e $P_t + \Delta P_{2-x}$ (14)

Fan velocity pressure/ Fan static pressure

Fan velocity pressure is the pressure corresponding to the average velocity at fan outlet

$P_v = (Q_2/109.7A_2)^2\rho_2$ (15)

The Fan static pressure; this is the difference between the fan total pressure and the fan velocity pressure. Therefore, fan static pressure is the difference between the static pressure at the fan outlet and total pressure at fan outlet. $P_s = P_t - P_v = P_{s_2} - P_{s_1}$ (16)

If the fan draws air directly from the atmosphere $P_s = P_t - P_v = P_{s_2}$

Fan speed

The fan speed simply refers to the relative speed of the impeller.

Compressibility factor

This is the ratio of the fan total pressure $P_t^{'}$ that would develop for an incompressible fluid to the fan total pressure P_t that is developed for a compressible fluid when all other conditions remain the same.

$K_p = P_t^{'}/P_t = n(n-1)[(P_{t2a}/P_{t1a})^{n-1/n} - 1]/(P_{t2a}/P_{t1a})$ (17)

Compressibility factor may also be determined by measurement using

$X = \rho_x/\rho_{t1a}$ (18)

$z = [(\gamma - 1)/\gamma]$ 6.356H/(QP_{t1a}) (19)

Then $K_p = [zlog(1+x)]/[x \log(1+z)]$ (20)

Fan power input, output / total fan efficiency $(\boldsymbol{\eta_t})$

This is the power require to drive the fan and elements in the drive train which is considered a part of the fan. Fan power input can be calculated from appropriate measurements using a dynamometer, torque meter or calibrated motor.

However, the fan power output is expressed as $H_o = QP_t\,K_t/6356$ (21)

The total fan efficiency is given as;

$3\eta_{t=}QP_tK_p/(6356H)$ (22)

or $\eta_t = \omega_t/\omega_{sh}$

Fan static efficiency $\boldsymbol{\eta_s}$

The fan static efficiency is expressed as a function of the total fan efficiency, fan static pressure and fan total pressure. The relationship is expressed below;

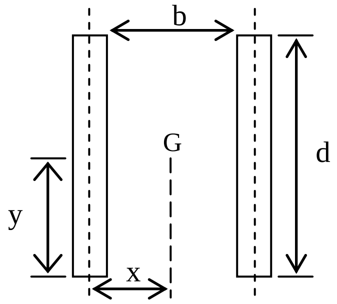
$\eta_s = \eta_t P_s/P_t$ (23)

Fan sound Level

The sound Level is ten times the logarithm (in base ten) of the ratio of the actual sound power in watt to 10^{-12} watts. $L_w = 10\log(w/10^{-12})$ (24)

1.1.3 Carrying capacity of tray

The slot carrying the frame will be welded to the main frame of the drying chamber. The characteristic of the welded tray supports and of the tray itself are given below.



Throat Area	Location of G	Unit of polar moment of inertia
A = 1.414bd	X = b/2 Y = d/2	$I_u = d(3b^2+d^2)/6$

Figure 1. (weld diagram and design considerations of the tray section)

Primary shear force produced in the weld $\tau' = S_f/A$ (25)

The Moment M_1 due to the weight of the commodity to be dried (assume to be concentrated at the centre of the plate) produces a normal bending stress τ_b in the welds. It is normal to assume that this stress acts normal to the throat area, during weld analysis.

Unit moment of inertia $I_u = d(3b^2 + d^2)/6$ (26)

Moment of inertia on throat area

$J_t = 0.707 J_u$ (27)

$\delta = M_c/1$ (28)

The factor of safety of guarding against static failure in the weld metal is $n = s_y/\delta$ (29)

1.1.4 The Control System

The control system is an integral system that monitors the condition within the drying section of the machine such that when the condition indicates a dry state, it by means of manipulation of a programmable logic and control (PLC) network, sets off the shutdown process. The control system is a logic assembly of the major components of the machine such as the actuator motor and the heating element. The sensor which is an electronic device monitors the moisture level within the drying chamber and interprets it is as a voltage drop and then sends this signal to a comparator which is compared with the voltage drop across the motor coil when a zero voltage is recorded at the comparator over a time stretch, the time on De-energizing control units sends a confirmatory shutdown signal to the power unit. Meanwhile, a unit feedback loop continually relates the system response signal back to a summation point (or a comparator) which also works like the former. The control system, in effect, is a two way system which maximizes its performance. A moisture detector could be fitted into the drying chamber in order to measure the moisture level in any commodity that is been dried. When the commodity is sufficiently dried, the moisture detector will trigger a system (by sending an analogue or digital signal is a robotic arm) for instance, that will turn off the drier and the blower. The system arrangement is diagrammatically shown below:

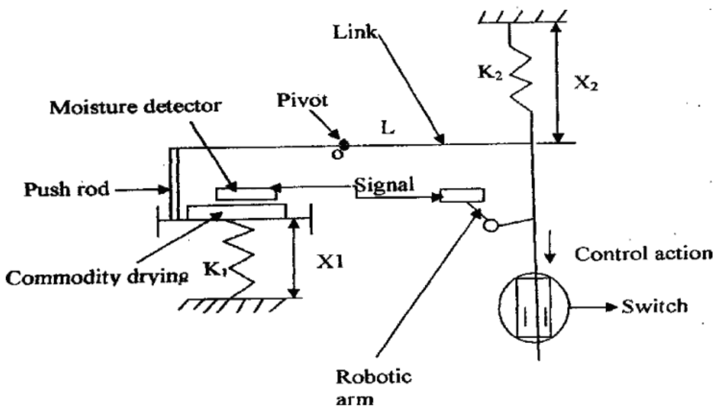


Figure 2. Control system arrangement

1.1.5 Heating Element Dimensioning

Nichrome wire and Nickel-Chrome are most widely used heating element. They can be safely heated above 1000°C and their emissivity is 0.09 each. Their radiating efficiency is in the neighbourhood of 0.5. For primary design calculations, the following holds:

Heating element material: Nichrome
Charge of the heating element: 30°C
Final temperature: 800°C
Radiating efficiency: 57%
Specific resistance of Nichrome: 109×10^{-8} Ωm
Source of electricity supply (domestic use): 220V, 650W

$$L/d^2 = \pi\, v^2/4\rho P \tag{30}$$

$$L/d = 53653170.23$$

$$H = 5.72\ ek[(T_1/100)^4 - (T_2/100)^4] = 38870$$

$$H = 11.49m\ and\ d = 0.0045m = 4.5mm$$

1.1.6 Heating Chamber Length and Pumping Power of Blower

The cross- section of the heater tube is given as D = 200 mm = 0.2m
The air temperature reaching the commodity was about 40°C
The air velocity is about $3 - 5mls$
The air entering the blower is at 15°C
The Reynolds analogy will be followed in the design process
The friction factor is calculated by f = $0.0791(Re)^{-1/4}$ (31)
The air properties are considered at the mean temperature

$$\Delta t_n = (\Delta \mathrm{t}_1 - \Delta \mathrm{t}_2)/\ln(\Delta \mathrm{t}_1/\Delta \mathrm{t}_2) \tag{32}$$

II. RESULTS AND DISCUSSION

Calculation:

The mean film temperature is given as $t_f = (t_b + t_w)/2 = 413.15°C$
The properties of air at $t_f = 686.75\ K$ (from table)
We have prandtl number $p_r = 0.681$
Kinematics viscosity of air, $k_i = 3.2 \times 10^{-5}$ m²/s
Air density, $\rho_{air} = 0.73kg/m^3$
Thus, Reynolds number $R_e = CD/K_i$

(33)

$$R_e = 31250$$

$R_e 31250 > 2000,$ Confirms that the flow is turbulent

$$F = 0.00595$$

Staton number is given as $s_t = \frac{N_u}{R_e P_r}$

(34)

$$s_t = \frac{F}{2} = 0.002975$$

$$N_u = 63.312$$

$$\alpha = {N_u}^* \lambda/d = 0.04$$

Mass flow rate of air m $= \rho AV = 0.57kg/s$
Where Q = $\propto A\Delta t$

(35)

$$Q = mc(t_{a2} - t_{a1})$$

(36)

$$Q = 14.72kw$$

$$\Delta t_n = 772K$$

$$L = 72cm$$

$$A = 1.70cm^2$$

The Pumping Power of the Fan is $W/Q = C^2/c\Delta t$

$W = P_{pumping} = 11.60\,W$

Flow rate of pumped air

$H_o = QP_tK_p/6356$ (37)

The SI unit system this equation reduces to $P = QP_tK_p$ and

$Q = 0.34\,m^3/s$

Free body diagram and shear force diagram

Figure 3 and 4 are representative of the free body and shear force diagram respectively.

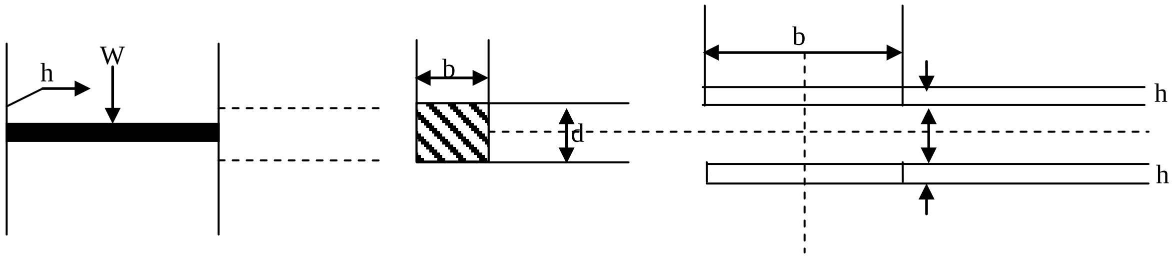
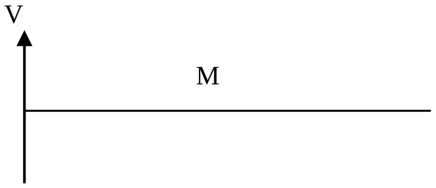


Figure. 3. The free body diagram at tray supported

The figure show the free body diagram at tray supported in both end by a supporting slot welded to the wall of the drying chamber. The free body diagram of one end of the tray will show a shear force S_f and reaction moment M (see below).



The primary shear in the welds is of magnitude

$\tau' = {}^{S_f}/_{A}$; (38)

A = 1.414hb (39)

Chosen b = 45 cm = 450 mm and h = 5mm

A = 3181.5 mm^2

Thus, with a maximum weight of 10 kg equally supported by both end S_f = 49.05N

The primary shear stress is $\tau' = 0.015MPa$

The bending moment diagram is shown below;

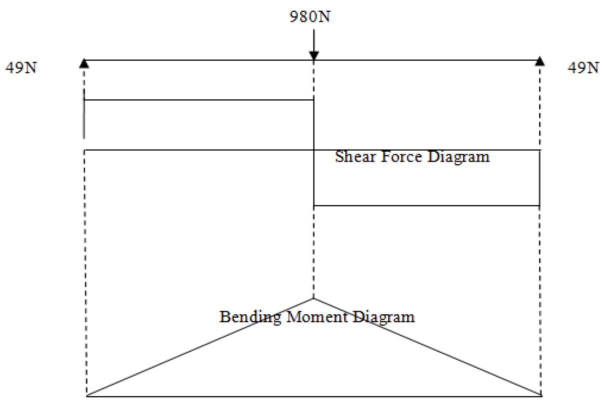


Fig. 4: Bending Moment Diagram

The maximum bending occurring at the center of the tray is given as
M= 9800 Nmm,
The unit polar moment of inertia is

$$\delta_u = \frac{d(3d^2+d^2)}{6} \tag{40}$$

$$\delta_u = 3042000\ mm^4$$

The polar moment of inertia base on the throat area (equation) is given as

$$J = 707h\delta_u \tag{41}$$

Substituting values of h and, $J = 10753470\ mm^4$

The centroid of the weld is located at

$$X = b/2 = 225mm$$

$$Y = d/2 = 15mm$$

We can fine the secondary shear stress in components parallel is x and y, the component of y is;

$$\tau_y'' = \frac{MY}{J} \tag{42}$$

$$\tau_y'' = 0.2Mpa$$

The component x is;

$$\tau_x'' = MY/J = 0.0136MPa$$

These stress components should be combined to yield the maximum stresses; which occur at both end of the tray in the welds

$$\tau = \sqrt{\tau_x'' + \tau_y''} \tag{43}$$

$$\tau = 0.21\ MPa$$

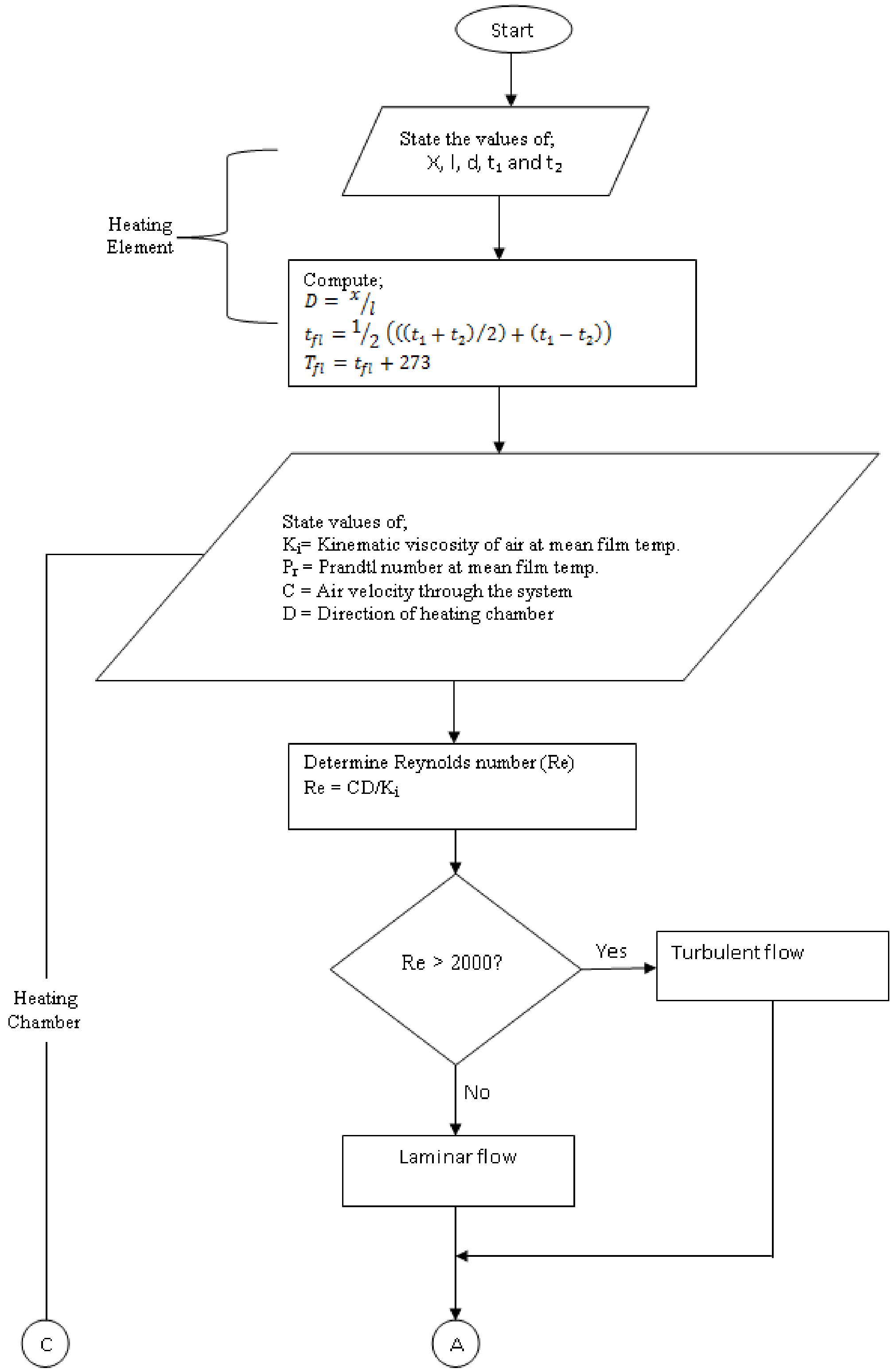
Chosen AWS electrode E60xx, the tensile strength= 62 kpsi
Yield strength =50 kpsi
Elongation percentage =17-26% (Data based on the America Welding Society specification standard), if we base the failure of weld on yielding, we have,
$S_y = 50\ kpsi = 3445\ MPa.$ The factor of safety guarding against static failure of the weld is provided by $n = S_y/\delta = 1640.4$

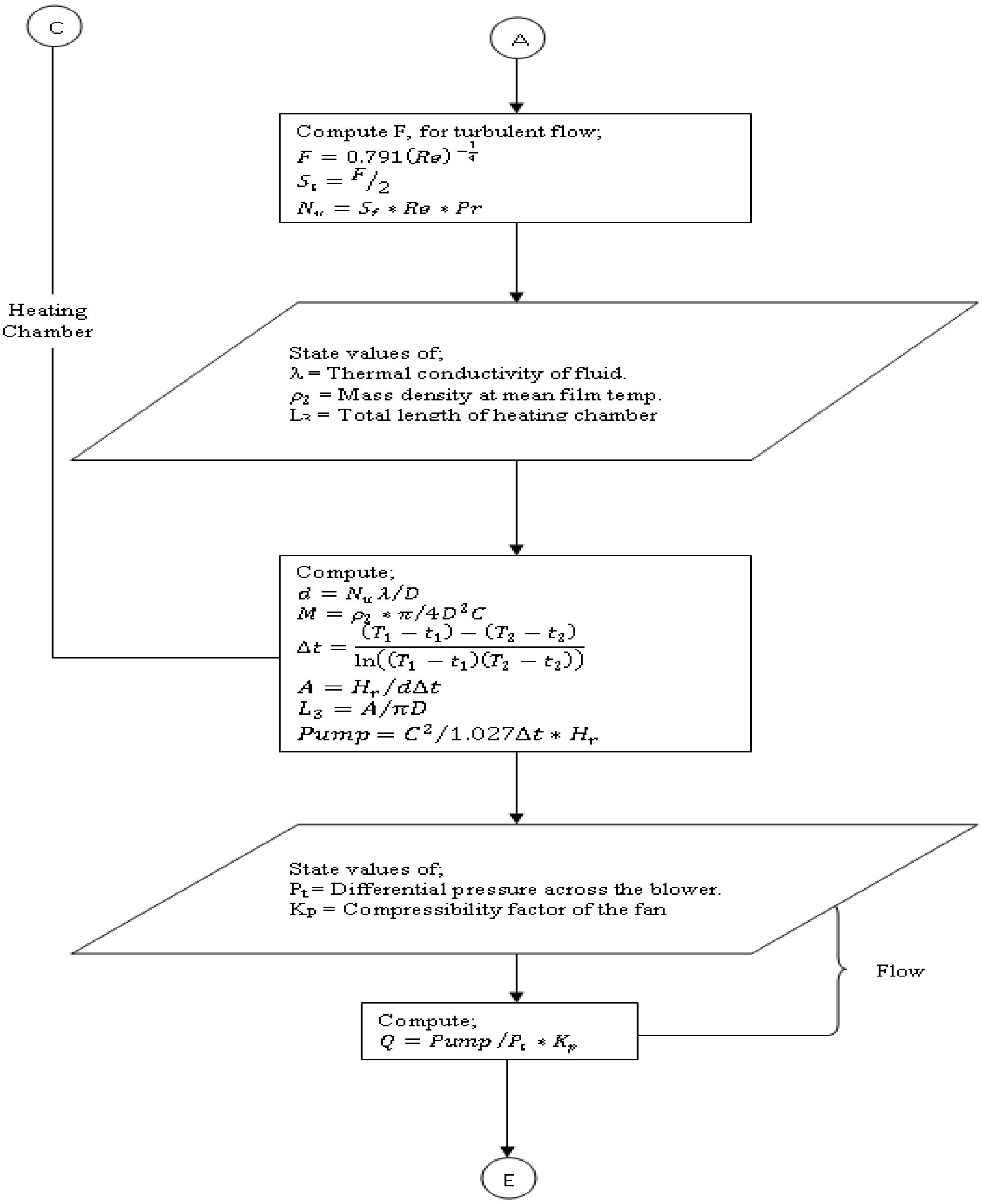
CONCLUSION

The value indicating total safety is somewhat large. This indicates that weld can support a load much greater than the 10 kg considered in the design calculations. However, the value of the maximum load that can be carried should be decided taking into account that the tray will bend after a certain limit of loading. This limit can be gotten theoretically but limiting constraint as the strength properties of the material available in the local market will decide on the maximum loads that can be carried. This system is a trade-off between efficiency and reliability. The result could be easily implemented, if any output parameter found is unacceptable by the program user, a new set of parameters can be computed into the program until an optimal design is obtained. The system occupies a total space of about 600 × 700 × 500 mm^3 and weight about 15 kg. A total of 30 kg can be dried at a time.

Appendix

FLOW CHART





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